Resilient Information Architecture Platform for the Smart Grid

Gabor Karsai, Vanderbilt University

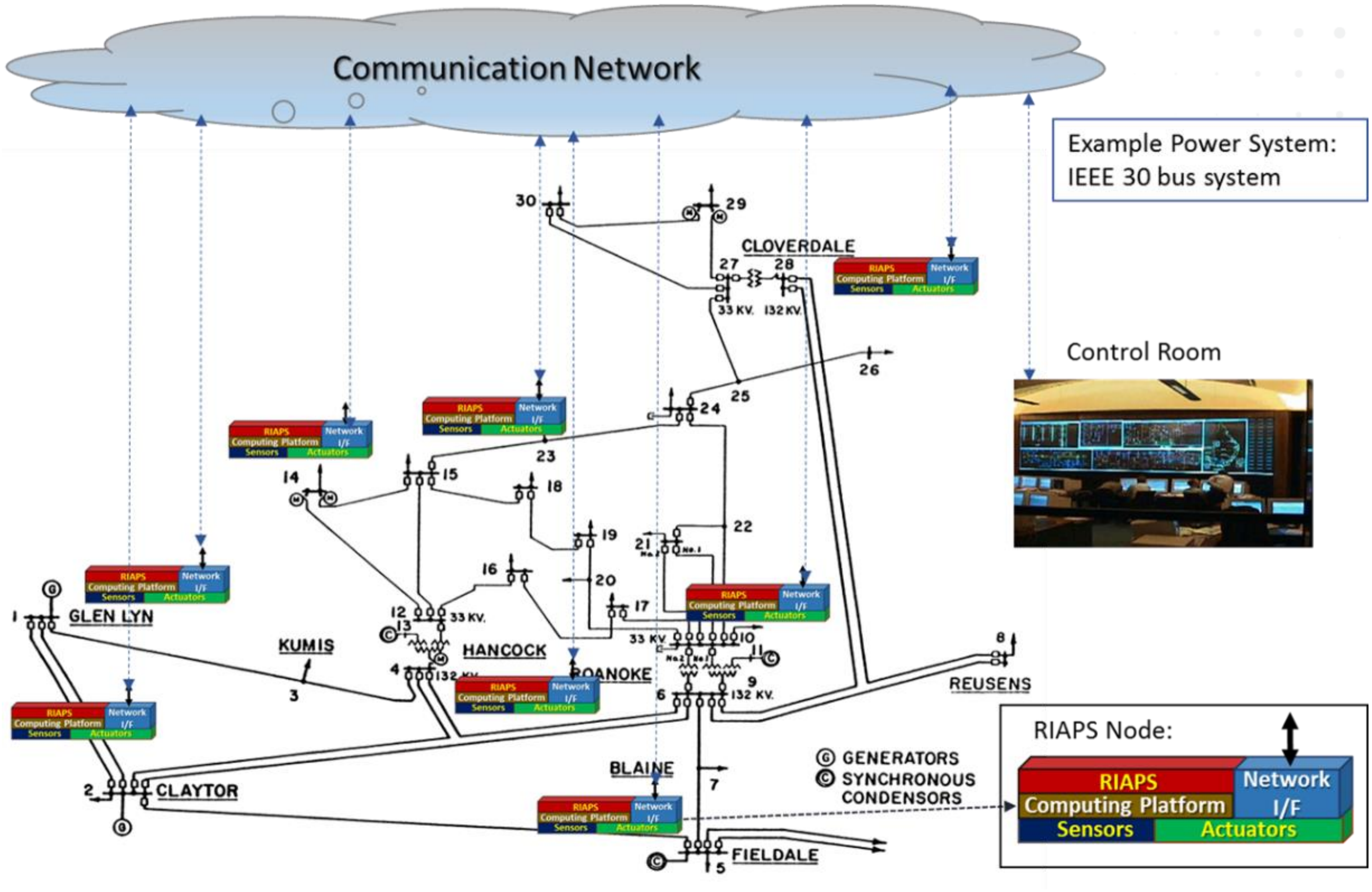
Network Optimized Distributed Energy Systems (NODES)
Annual Review Meeting

Feb 12-13, 2019

Project Summary

- **Goal**: To create an open source *software platform* to run Smart Grid applications and demonstrate it through *selected applications*. A software platform defines:
  – Programming model (for distributed real-time software)
  – Services (for application management, fault tolerance, security, time synchronization, coordination, etc.)
  – Development toolkit (for building and deploying apps)
- **Uniqueness**:
  – Focus on distributed *applications* - not only on networking
  – Focus on *resilience* – services for fault recovery
  – Focus on *security* – maintain confidentiality, integrity, availability

Project Summary



Project Summary

- **Challenges**:
  - How do we build *distributed fault tolerant smart grid applications* in a real-time context? – *It is more than a middleware or networking problem*.
  - How do we *manage* accidental complexities in the development process? – *Developers need tools to be productive*.
- **Deliverables:**
  - Software platform run-time: middleware and other libraries + services used by apps
  - Development toolkit for building, deploying, and managing apps
  - Example applications for the Smart Grid
  - Design documentation

Project Summary

- **Key outcomes**:
  - The *open source platform* will enable developers – sanctioned by utilities - to build reusable components and applications
  - The platform *specification* and its *prototype implementation* is open source, but for-profit entities will provide software development services for it
  - A new *open standard* that will change how software for the smart grid is developed
- Websites:
  - https://riaps.isis.vanderbilt.edu/ - Project
  - https://github.com/RIAPS - Code base
  - https://riaps.github.io/ - Documents
  - https://www.youtube.com/channel/UCwfT8KeF-8M7GKhHS0muawg - Youtube channel

Team

- Organizations: Vanderbilt University, North Carolina State University, Washington State University
  - Vanderbilt University (Prof. Gabor Karsai & Abhishek Dubey) Institute for Software-Integrated Systems has decades of experience in researching and developing middleware, model-driven development tools, real-time fault diagnostics, software platforms.
  - North Carolina State University (Prof. Srdjan Lukic, David Lubkeman) is home to the NSF Future Renewable Electric Energy Delivery and Management (FREEDM) ERC, have expertise in power grid based on power electronics, high bandwidth digital communication, and distributed control, including testing of experimental and commercial microgrid controllers
  - Washington State University (Prof. Anurag Srivastava, Chen-Ching Liu, Dave Bakken) has expertise in power system operation and control, hosts the Smart Grid Testbed (SGDRIL), does research on power systems operation in extreme scenarios, Smart City Testbed, and on fault tolerant computing and middleware for power systems

Team

- While all team members have electrical engineering background they specialize in complementary fields:
  - Distributed Real Time Embedded systems (Karsai and Dubey)
  - Fault Tolerant Computing (Bakken and Karsai)
  - Electrical Power Engineering (Srivastava, Liu and Lukic)
  - Cyber-Physical Testbeds (Srivastava, Liu and Lukic)
  - Control Engineering (Srivastava, and Liu)
- The team members have solid industry connections that will enable technology transition:
  - Help from industry advisory board to target the technology for the market
  - Ability to do hardware in the loop testing allows having product ready for field installation

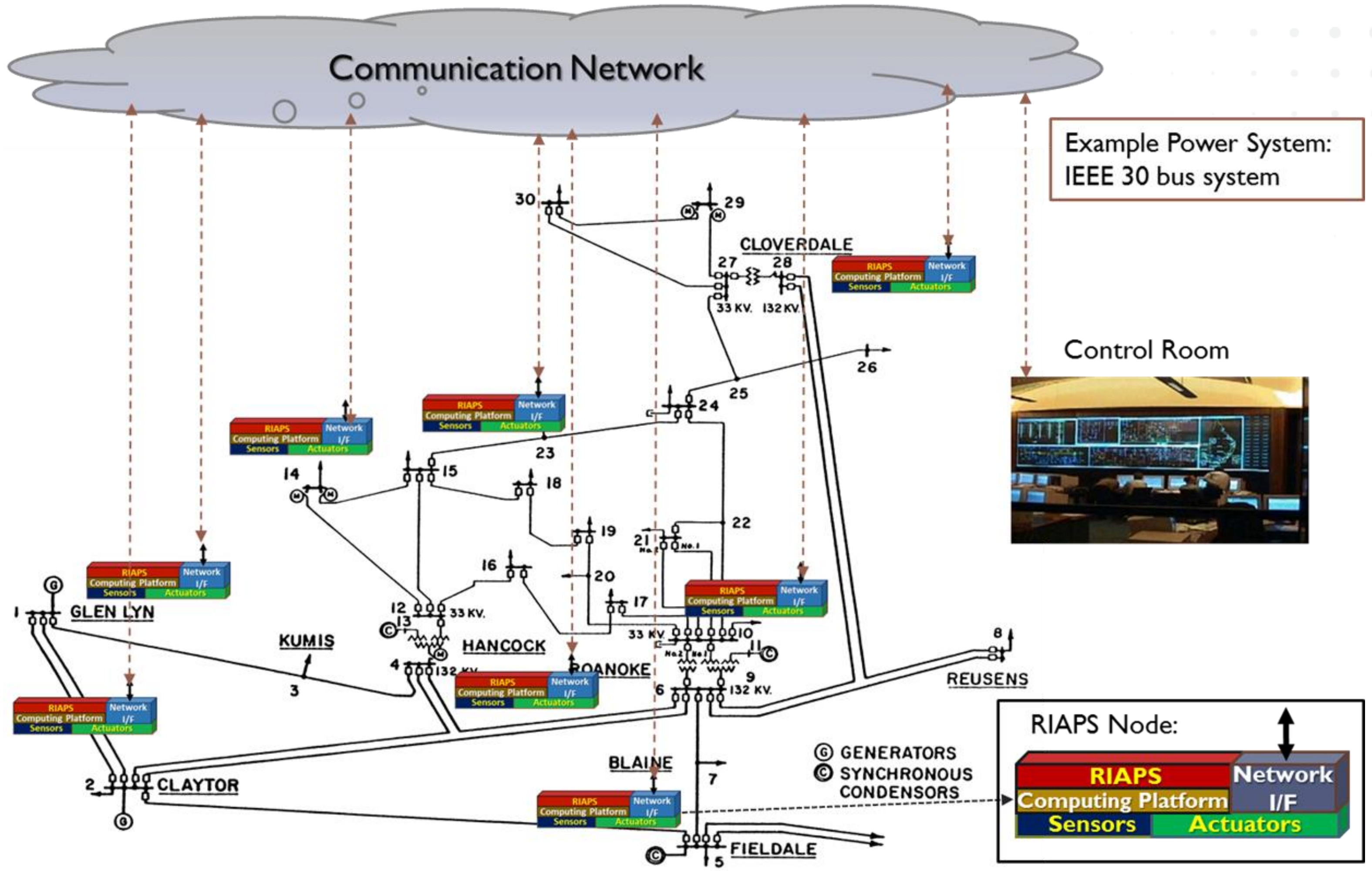
Project Progress

	PE	Year1	Year2	Year3	Status
1	Analysis, Design, Documentation				On track
2	Component Framework: Detailed Design, Implementation, Verification				On track
3	Platform Services: Detailed Design, Implementation and Verification				On track
4	Development toolchain design, implementation, verification				On track
5	Representative Applications Development and Evaluation				On track
6	Technology Transition				On track
	Demonstrations				On track

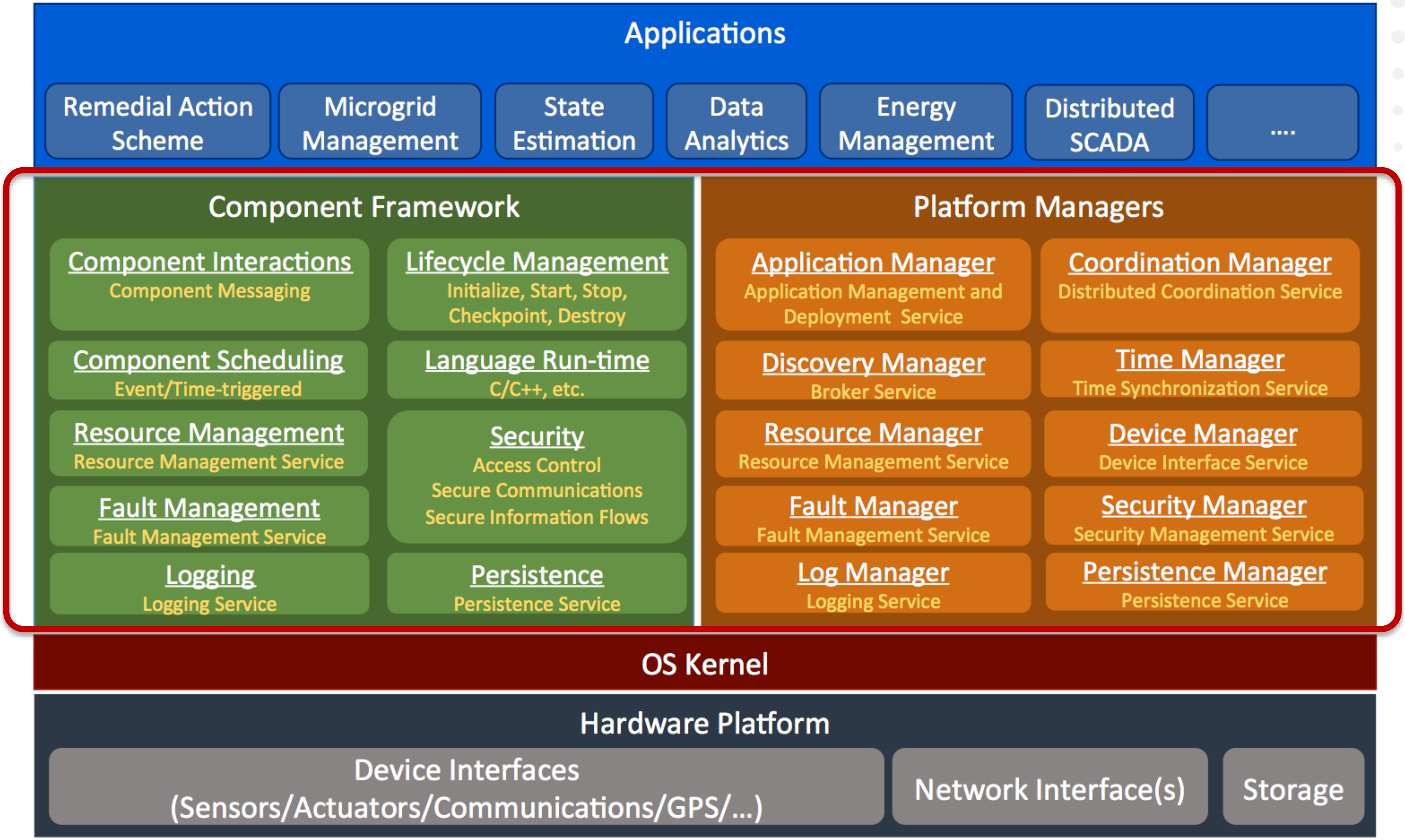
Validation Plan - Summary

- HIL system
  - For RIAPS (software platform):
    - Development platform: Linux
    - Target platform: Beaglebone Black (embedded ARM)
  - For RAS (WSU):
    - Simulation: RTDS + Target platform (BBB)
  - For Microgrid control (NCSU):
    - Simulation: Opal-RT + Target platform (BBB) + DSP
- Managed DERs:
  - RAS: Wind farm
  - Microgrid: PV, Batteries (via inverter)
- Test plan
  - Platform: M1.2.1, 1.5.1, 1.7.1, 1.9.1., 2.1.2/4, 2.2.1/3, 2.3.3, 3.1.2/3/5, 3.2.2/4, 3.3.4, 3.4.2, 4.1.3, 4.2.1-3,4.3.1/3, 4.1.3
  - RAS: 5.8.1,5.9.2/3,5.10.1,5.11.1/2,5.12.1, 5.12.2
  - Microgrid: 5.2.1,5.3.1,5.4.1,5.5.1,5.6.2
- Field validation test sites:
  - Discussions with IAB members
  - VMWare/LF Energy
- Large scale simulation plan: RTDS + Opal-RT

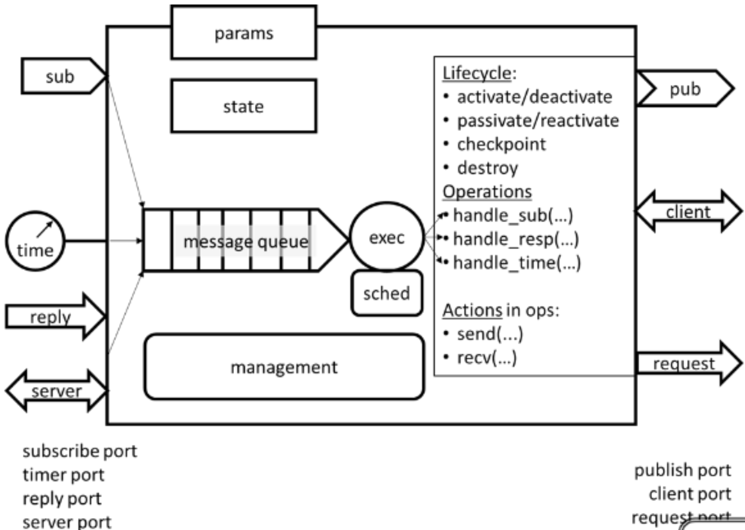
Vision
Distributed Computing for the Grid



RIAPS
The Software Platform

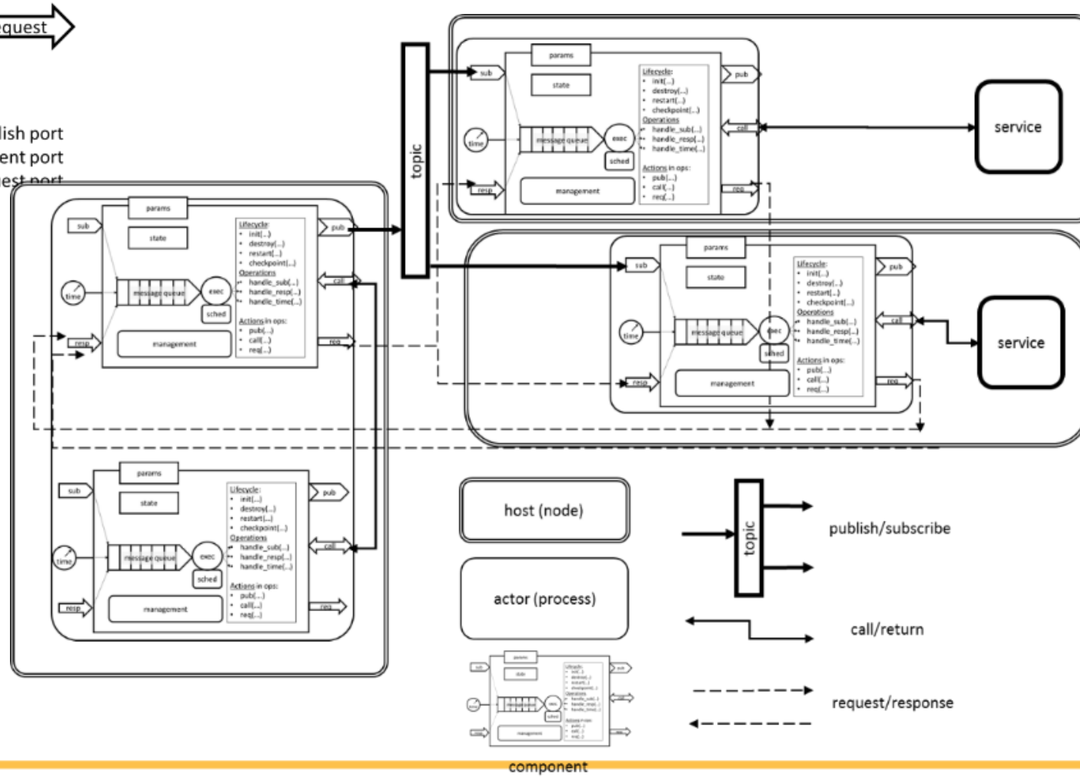


RIAPS apps
Components + Actors



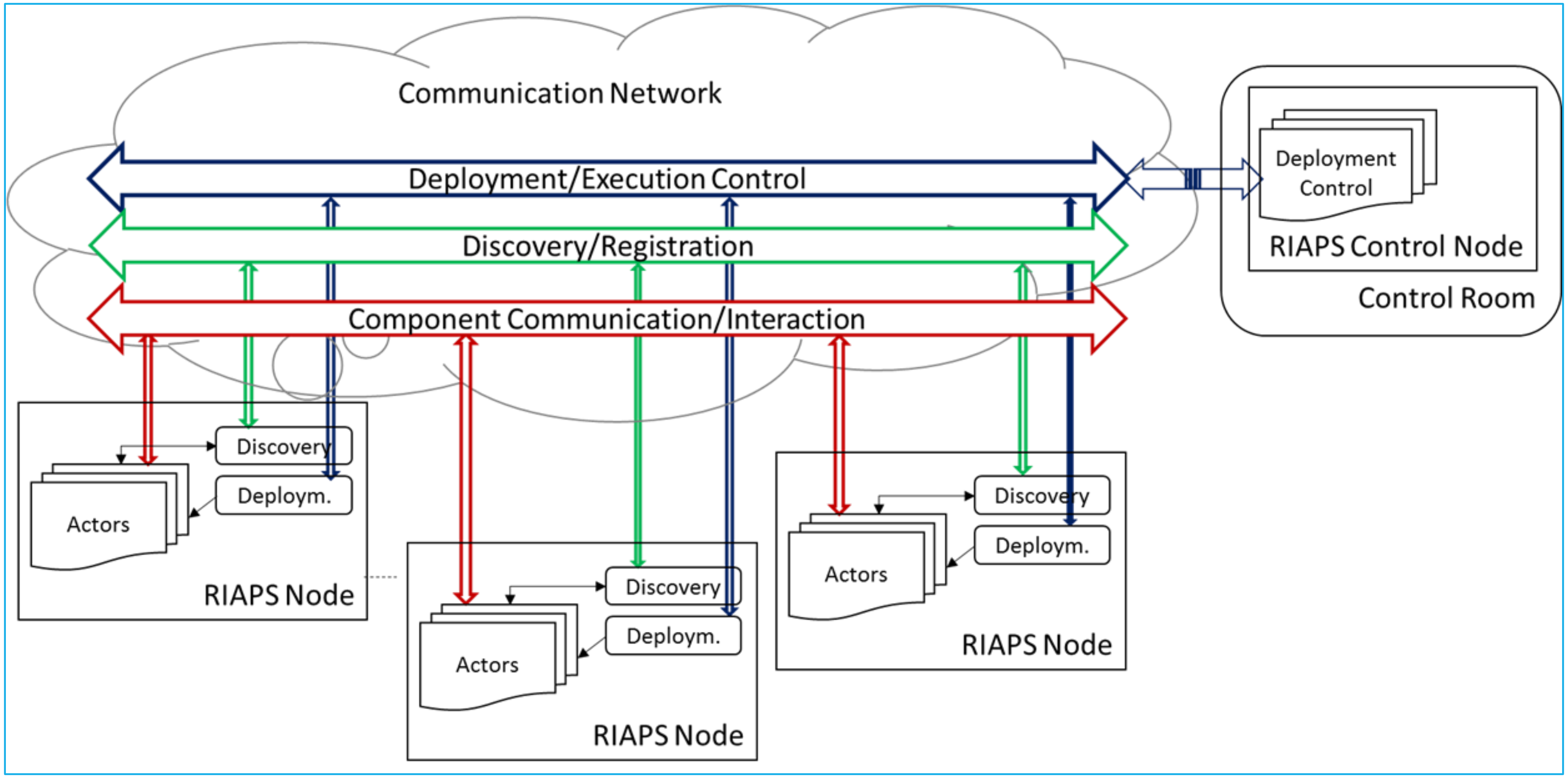
Components are the building blocks: defined interfaces (ports) + execution semantics – simple code, may encapsulate complex applications (e.g. numerical solvers) in Python/C++

Actors are built from components that interact solely via messages and are deployed on computing nodes in a network.
All applications are built as a fabric of interacting components



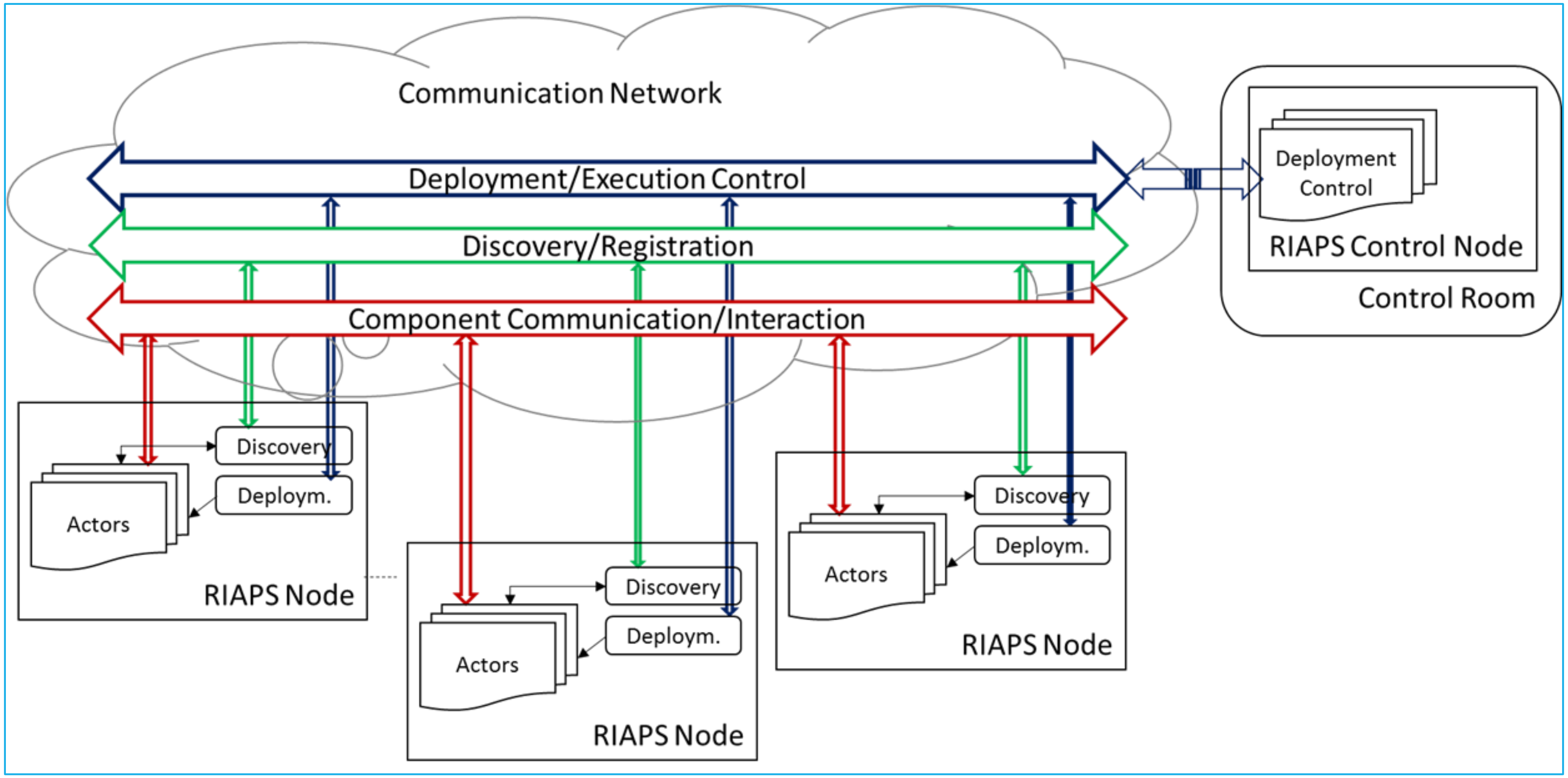
RIAPS services Deployment

- **RIAPS nodes and apps**
  - are managed by a system operator (control room)
  - can join and leave the network at any time



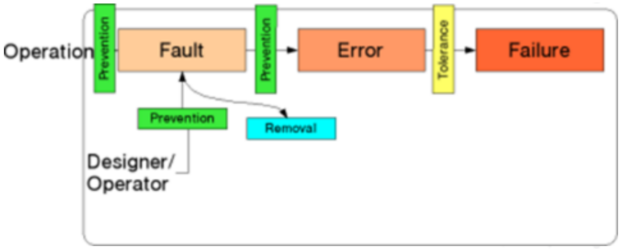
RIAPS services Discovery

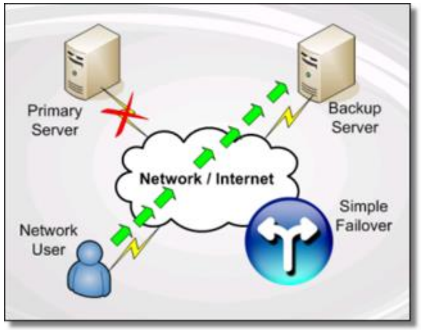
- **RIAPS components form a peer-to-peer network, organized and configured via the Discovery service**
  - Service provider – service client match-up



RIAPS services
Fault management

- **Assumption**
  - Faults can happen anywhere: application, software framework, hardware, network
- **Goal**
  - RIAPS developers shall be able to develop apps that can recover from faults anywhere in the system.
- **Use case**
  - An application component hosted on a remote host stops permanently, the rest of the application detects this and ‘fails over’ to another, healthy component instead.
- **Principle**
  - The platform provides the *mechanics*, but app-specific behavior <u>must be </u>supplied by the app developer





RIAPS services
Distributed Coordination

- **Group membership:**
  - An app component can dynamically create/join/leave a *group* that facilitates fast communication among members
- **Leader election:**
  - A group can ‘elect’ a *leader*: a component that makes global decisions. Election is automatic and fault tolerant, group members directly interact with the leader.
- **Consensus:**
  - Group members can ‘vote’ in a *consensus* process that reaches agreement over a value.
- **Time-coordinated control action:**
  - Group members use a combination of the above three features to agree on a *control action* that is executed at a scheduled point in time in the future
- **Application example – Microgrid control**
  - Group Membership and Leader Election: ‘microgrid’ groups for sharing information for better control
  - Consensus: on voltage and frequency values
  - Time-coordinated control action: microgrid to islanded mode

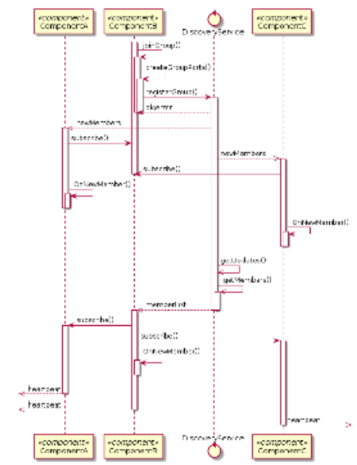
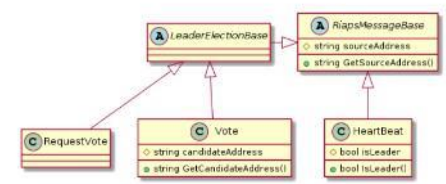
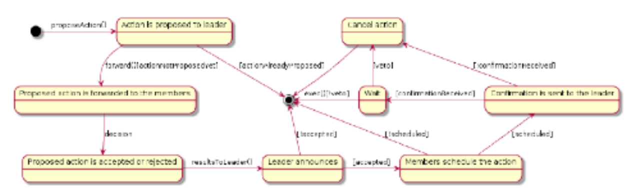


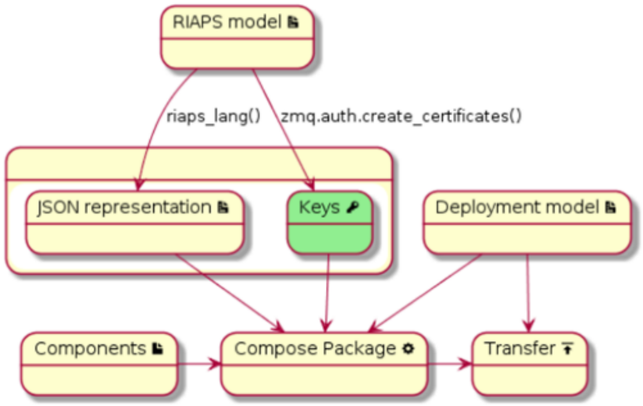
Figure 6: States of the leader election

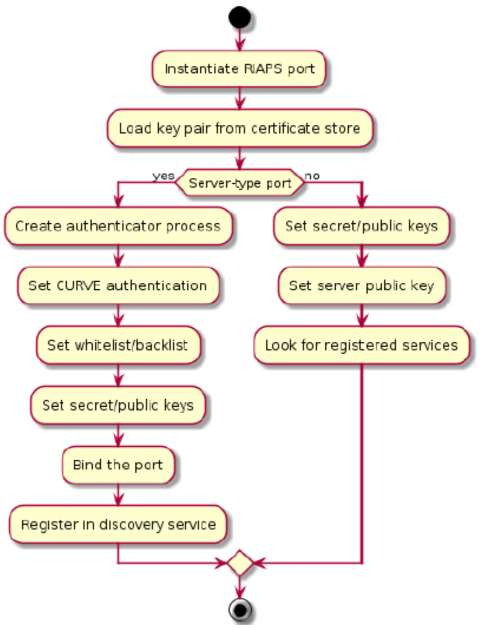




RIAPS Security Application deployment

- **Secure applications**
  - Application packages are compressed, encrypted and cryptographically signed before deployment. The recipient nodes verify cryptographic signatures, decrypt and install the app.
  - All app-level communications are protected by the CurveCP (elliptic curve encryption) on the messaging layer: ZeroMQ. All communications are protected via public/private keypairs, that are generated dynamically when the app is deployed. Keys are installed whenever an app-level network connection is established, and they are part of the deployment package, stored in a certificate store on the target nodes.

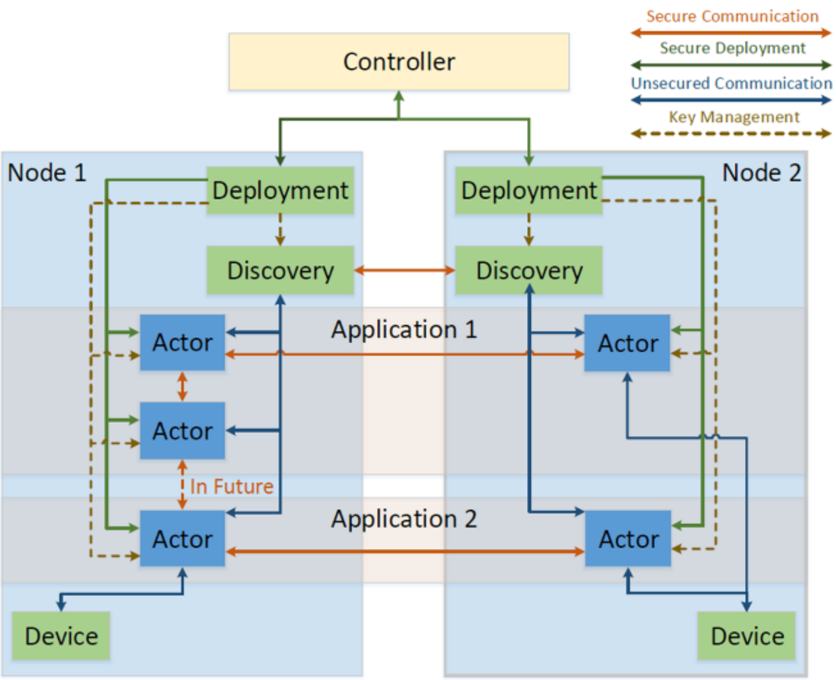




CHANGING WHAT'S POSSIBLE

RIAPS Security
Secure deployment / communications

- **Secure messaging between services**
  - Unsecured – communication is among processes on the same host
    - Deployment service ←→ actor
    - Deployment service ← → discovery service
    - Actor ←→ discovery service
  - Discovery service
    - OpenDHT already encrypts all service registrations
    - Discovery service instances use a single shared key across the network
    - Private key on node is protected via file access control



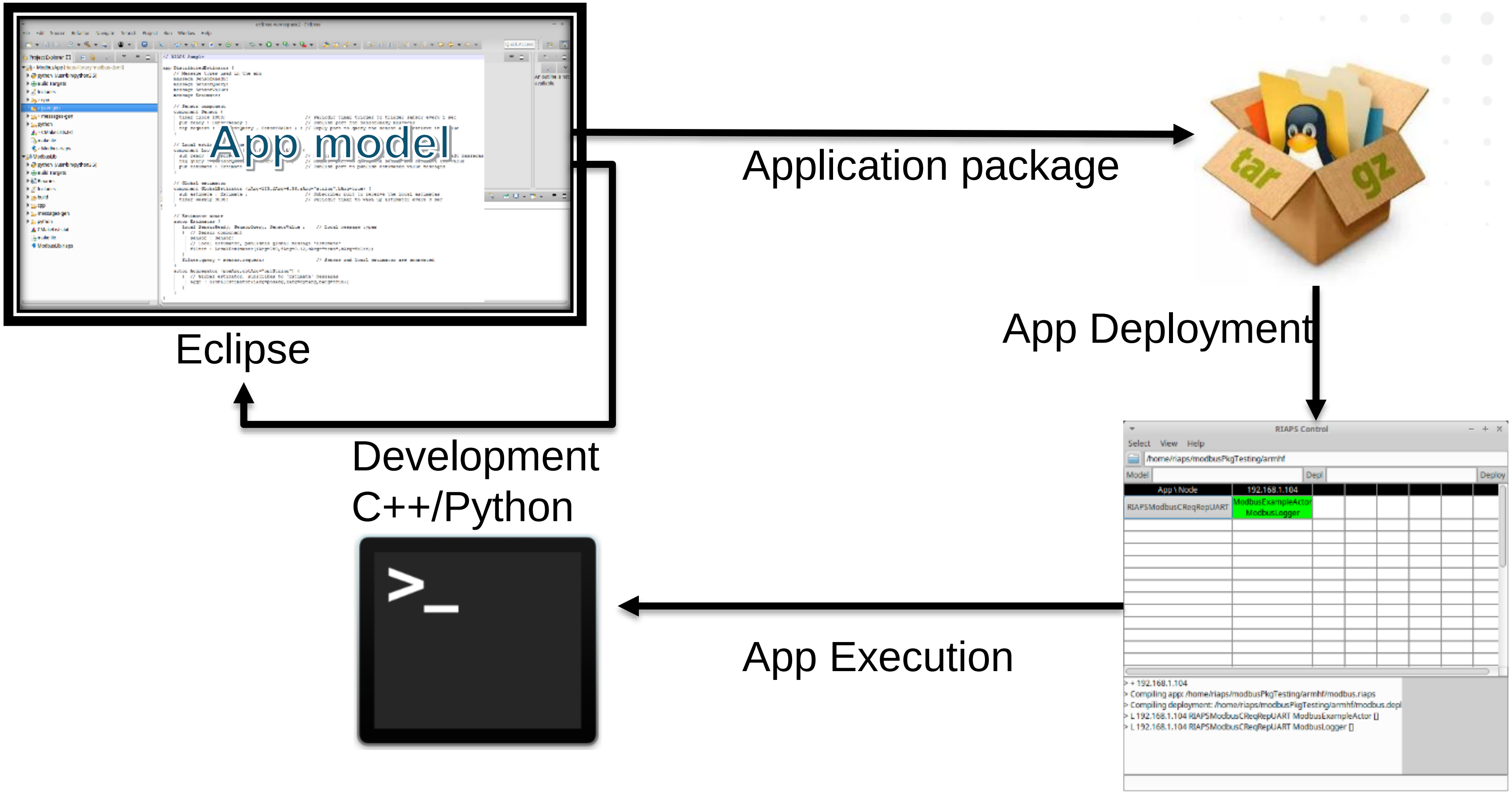
RIAPS Security
Application level protection

- **Network threats**
  - Each app actor is allowed to accept network packets only from hosts participating in the same app
    - App-level firewall on the incoming messages
- **Insider threats (malicious / flawed app)**
  - Network protection
    - App’s view of the network is explicitly modeled and used in configuring firewalls on the hosts
    - Firewall allows only communication within the RIAPS app’s network (both direction)
    - Exceptions are configurable by system integrator (‘owner’)
  - Information flow protection
    - AppArmor (a Linux Mandatory Access Control [MAC]) system is used to constrain the app’s access
    - Security profile is enforced by the trusted installer (Deployment Manager)
    - Default access: own files, core system packages, TCP/UDP protocols – very constrained – maybe necessary to allow app-specific overrides

RIAPS Security Test plan

Category	Layer	Feature	Test for
Secure Information Flows	Transport (ZeroMQ)	Key management	Key distribution for app communications Uniqueness of keys
		Authentication	Connection can’t be created without a proper key
		Encryption	No app information is shared in cleartext
		Integrity	No tampering with the message
		Denial of service	Resilience against typical DoS attacks (SYN flooding)
	Discovery (OpenDHT)	Key management	Key distribution for discovery service
		Authentication	Discovery service cannot be used without proper key
		Encryption	Unauthorized parties cannot access discovery All discovery messages are encrypted
		Denial of service	Resilience against typical DoS attacks (UDP flooding)
Application-level Security	Application manageme nt	Node configure	Node is properly configured
		Credentials	Application credentials are created
		Profile	Deployment service installs proper AppArmor profile
		Access Control	App can access only those services that are enabled by the profile

RIAPS Development Tools



For details please see: https://github.com/RIAPS/riaps-dsml

Application
RAS-1 for Minimum Wind Spilling

- Objective: To minimize wind curtailment while keeping the system reliability
- Constraints: Wind farm operational limits, line limits
- Distributed Implementation: Distributed Simplex Method in Linear Programming
- Offline simulation with N-1 computational block failure
- Verification with decentralized algorithm implemented in real time using CISCO Fog and Beaglebone Black

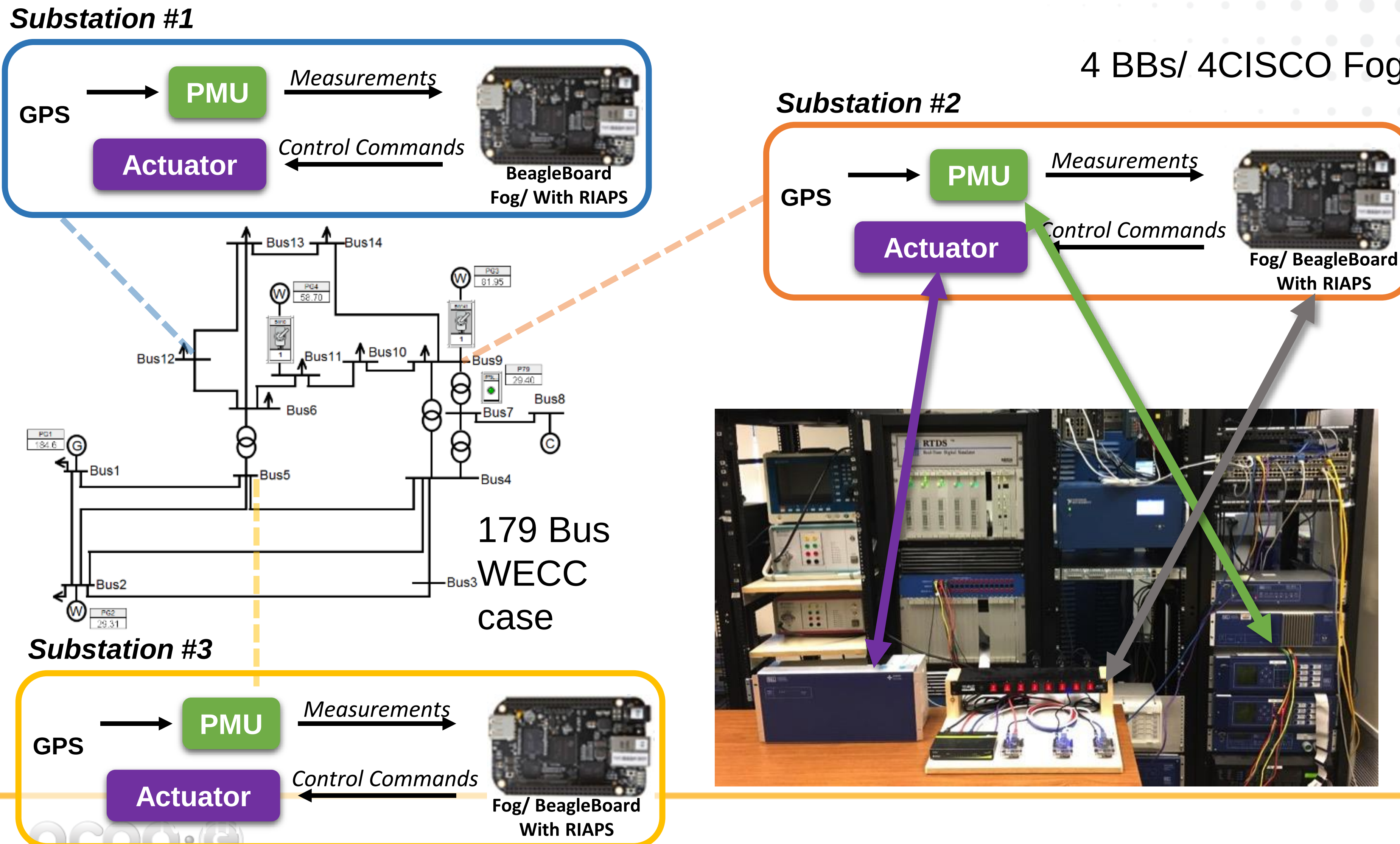
Mode of Operation	Wind Generation Curtailment	Execution time
All nodes operational	100.0 MW -> 84.14 MW	0.956s
Node failure	100.0MW -> 81.60 MW	1.035s

Items in Critical Conditions	Before RAS	After RAS	Limits Range
Voltage Magnitude at Bus #11	100.85%	99.81%	[0.94, 1.06] (*p.u.*)
Line Transferred Power from Bus #3 to Bus #4	98.76%	94.08%	[0, 50] (MVA)
Line Transferred Power from Bus #7 to Bus #9	122.69%	99.66%	[0, 35] (MVA)

- Without RAS, one of the transmission lines is overloaded by 16.6%.
- RAS algorithm curtail wind farm outputs and totally eliminated line overflows violation without any load shedding.

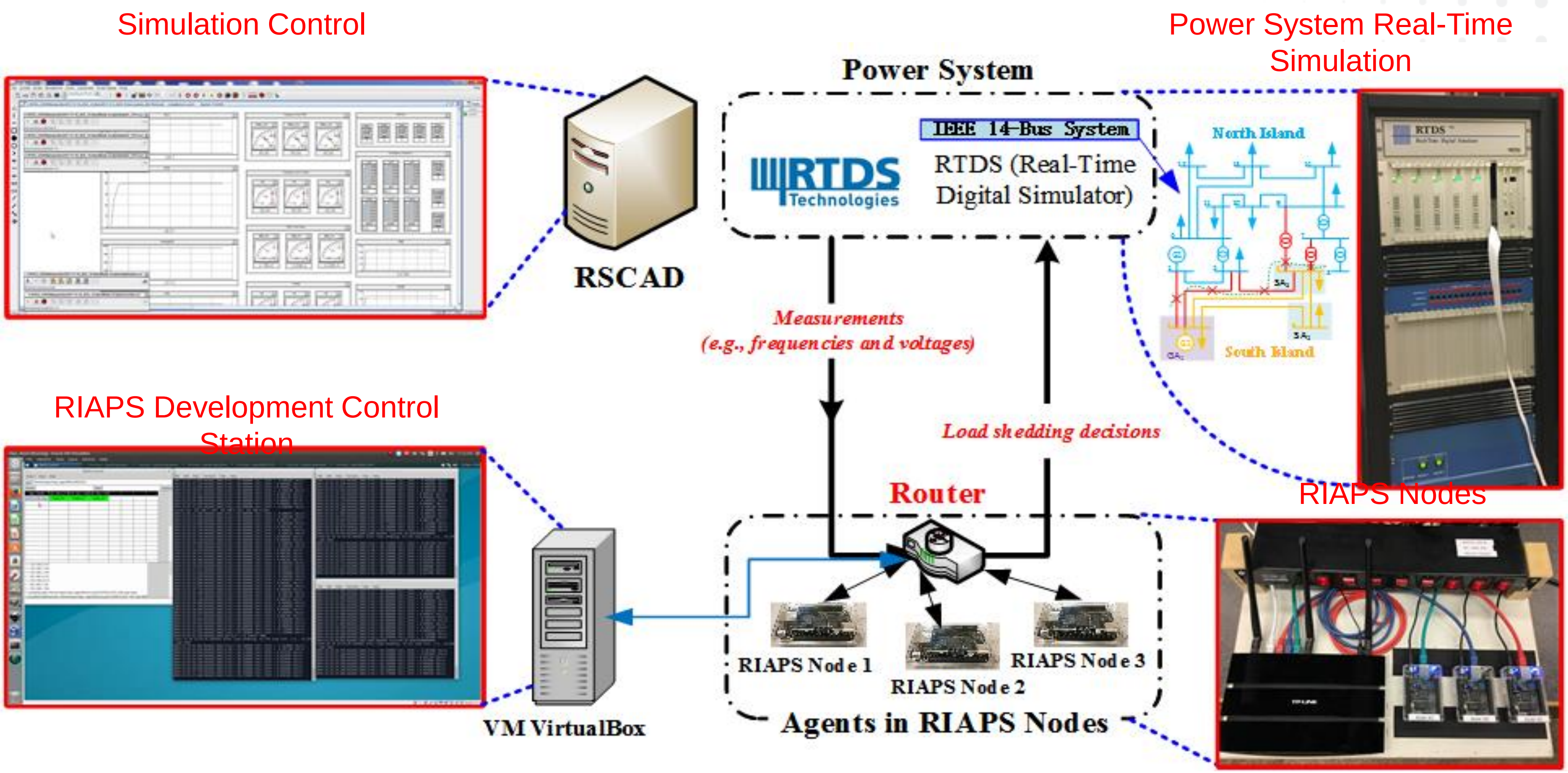
R. Liu, A. Srivastava, D. Bakken, A. Askerman, and P. Panciatici, "Decentralized State Estimation and Remedial Control Action for Minimum Wind Curtailment Using Distributed Computing Platform," IEEE Transactions on Industry Applications, Volume 53, Issue 6, Nov-Dec 2017, accepted 17 August 2017, pp. 5915-5926

Application
RAS-1: 179 Bus Case with Idaho Power



Application
RAS-2 : Optimal Under-frequency Load Shedding

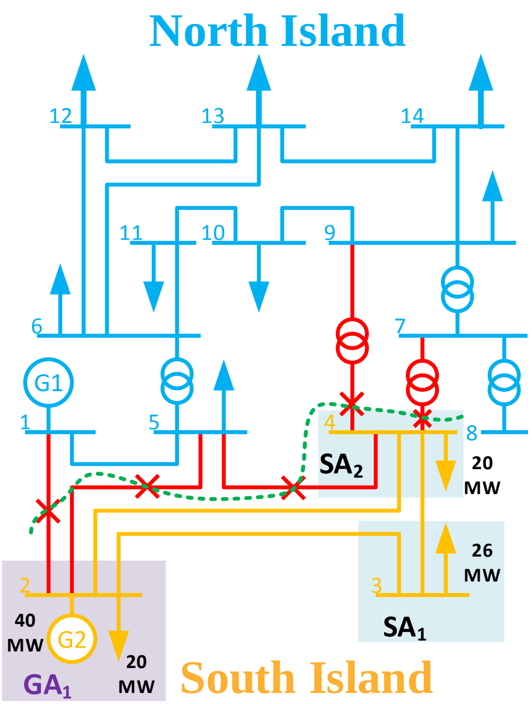
Real-time Simulation Architecture



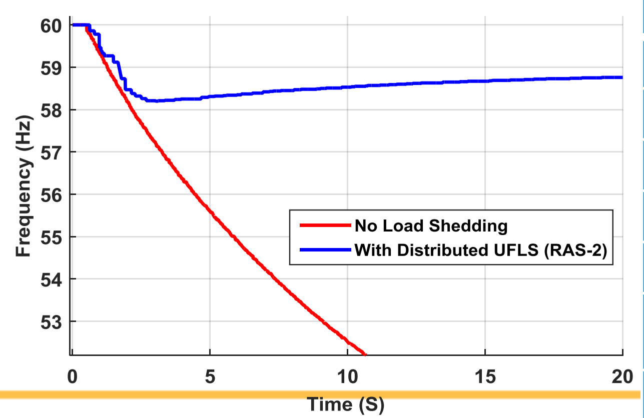
Application
RAS-2 for Frequency Control

Case Study

Modified IEEE 14-Bus System

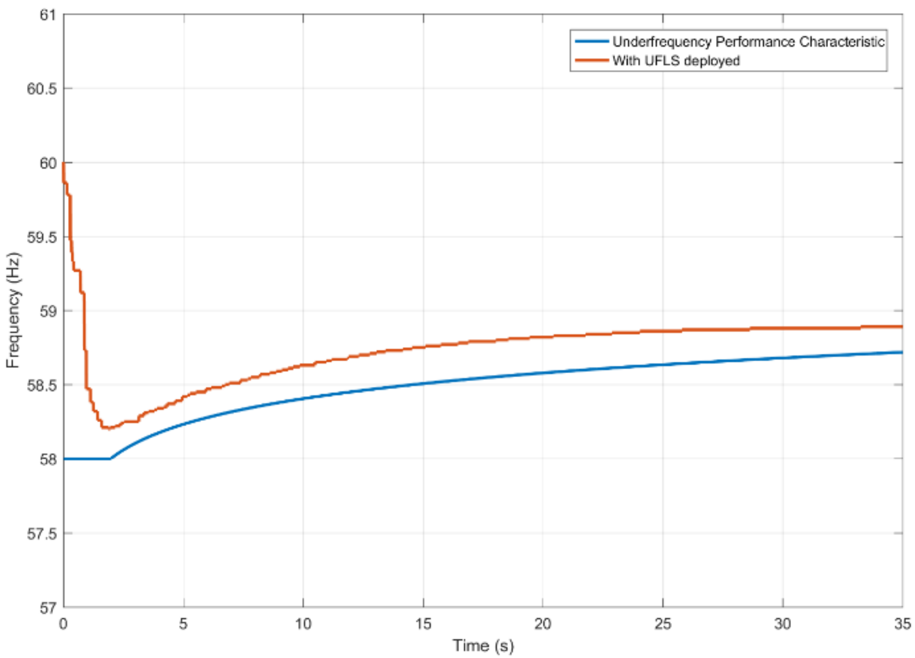


- Contingency Scenario
  - The power grid splits into two islands due to the tripping of three lines and two transformers;
  - The South Island is with an active power deficit.
- Simulation Results
  - (RTDS + 3 RIAPS nodes)
  - Without RAS, frequency drops quickly leading to the system collapse;
  - With RAS-2, the frequency decline is stopped at t = 3.04 sec.



UFLS schemes	With RAS-2	No RAS
Active load shedding (MW)	19.37	66
Reactive load shedding (MVAR)	9.58	32
Lowest frequency (Hz)	58.2	System collapse
Stable frequency (Hz)	58.89	System collapse
Time when frequency decline stops (sec)	3.02	System collapse
MW Reduction in load shedding compared with "No RAS"	70.65%	N/A
MVAR Reduction in load shedding compared with "No RAS"	70.06%	N/A

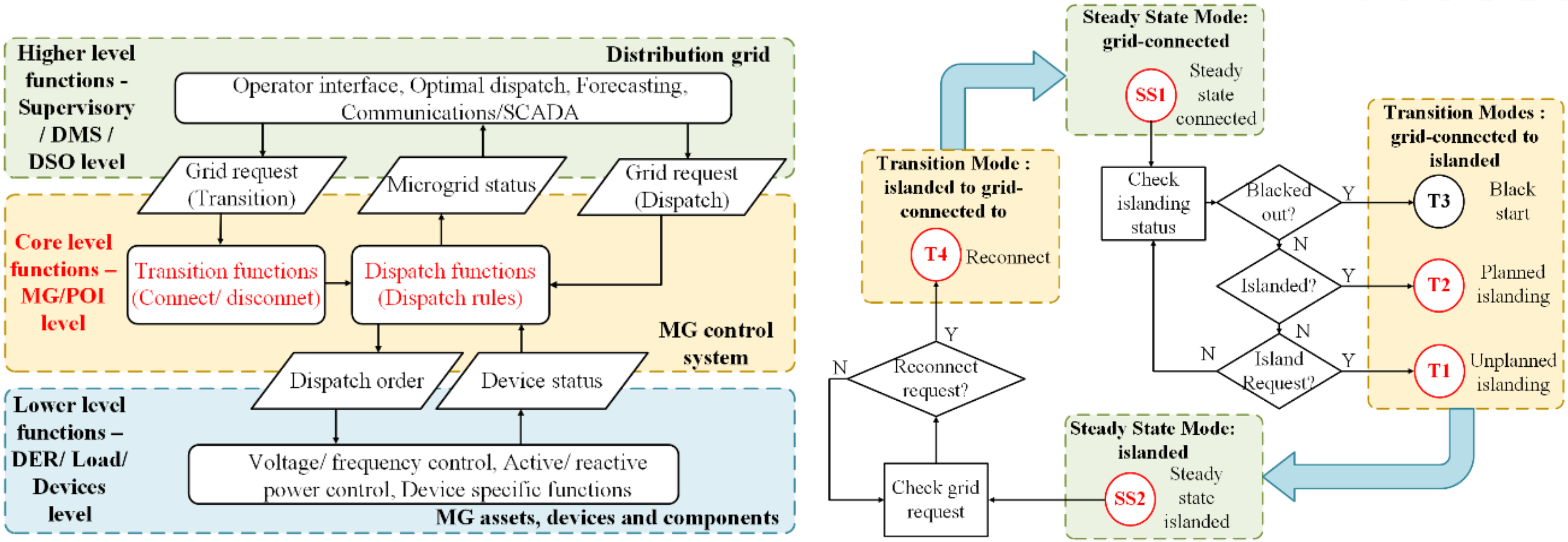
NERC PRC-006-1



Underfrequency Performance Characteristic		
t ≤ 2 s	2 s < t ≤ 60 s	t > 60 s
f = 58.0 Hz	f = 0.575log(t) + 57.83 Hz	f = 59.3 Hz

- The blue curve is the NERC under-frequency load shedding performance and modeling curve.
- The orange curve is the frequency response with RAS2.
- As the orange curve is above the blue curve, the NERC requirements are met.

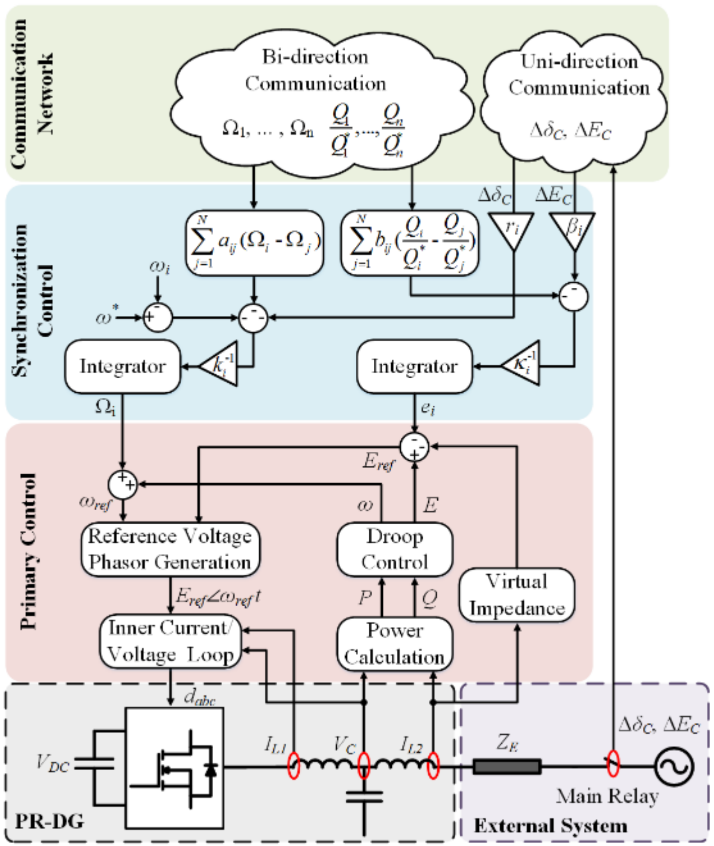
Application
RIAPS Microgrid Control System



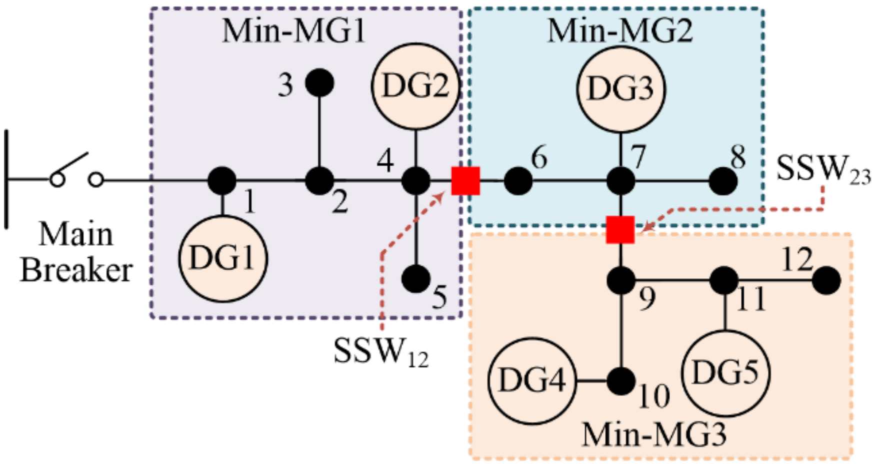
- Main challenge: provide stable operation in all operating modes
- Basic functionalities can be adapted to any microgrid topology (e.g. nested microgrids with moving boundaries).
- Focus on time-sensitive applications
- Energy management algorithms not the focus

Application
Microgrid Control System - Algorithms

- Yuhua Du, Hao Tu, Srdjan Lukic "Distributed Control Strategy to Achieve Synchronized Operation of an Islanded MG" Accepted to *IEEE Transactions on Smart Grid* (IEEE Early Access)

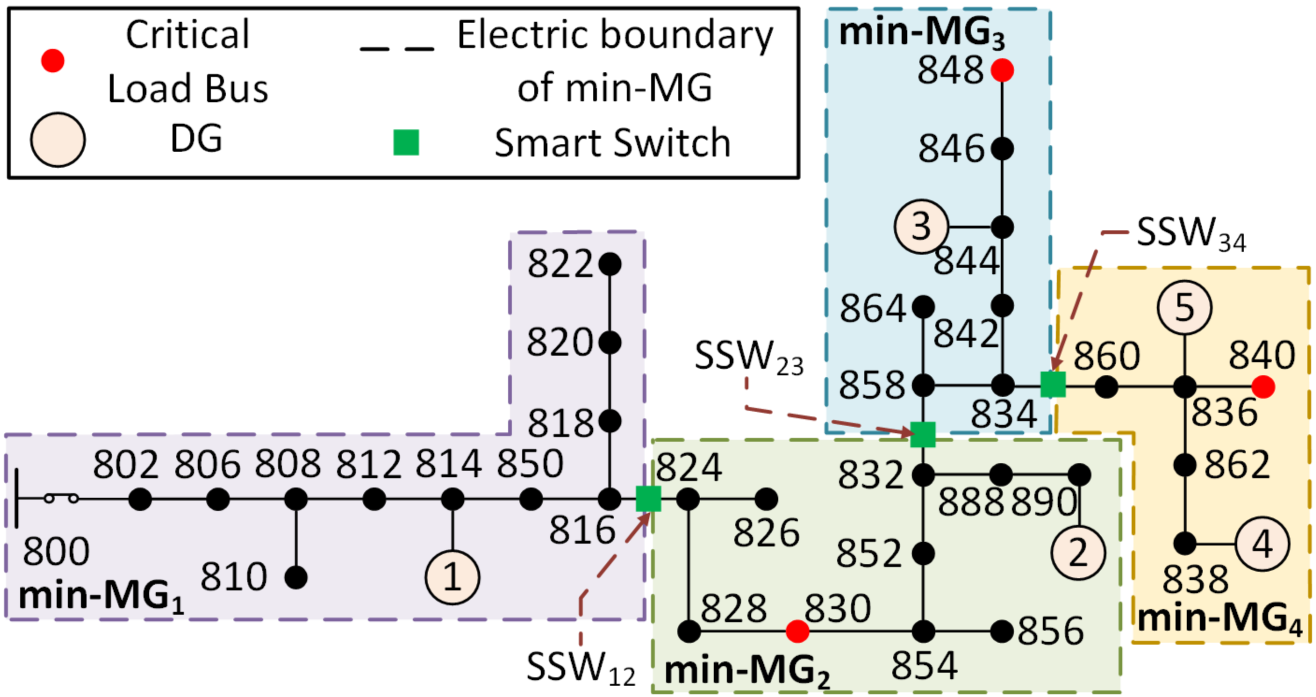


- Yuhua Du, Xiaonan Lu, Jianhui Wang, and Srdjan Lukic "Distributed Secondary Control Strategy for Microgrid Operation with Dynamic Boundaries" submitted to *IEEE Transactions on Smart Grid* (second review)

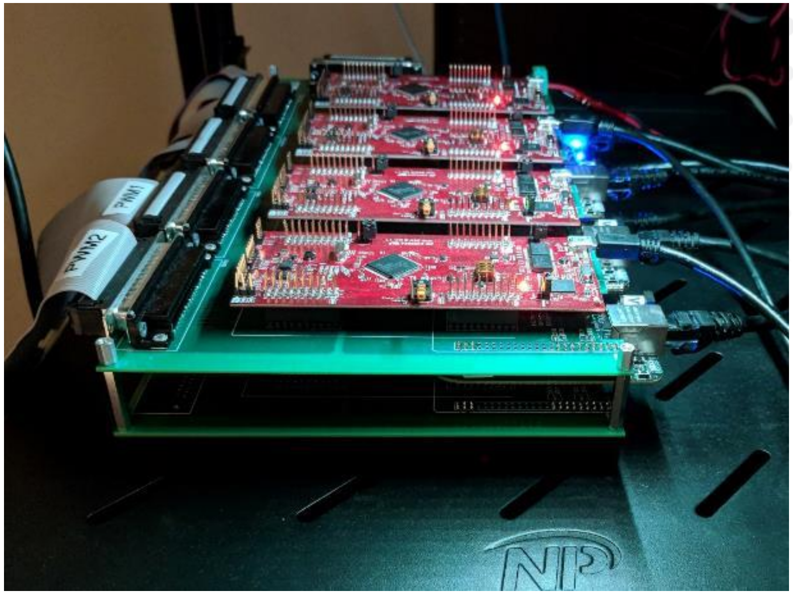


Microgrid Control System Advanced HIL Testbed

- Current work: Building the IEEE 34-bus system in Opal with unbalanced loads
- Implementing Distributed Secondary Control Strategy for Microgrid Operation with Dynamic Boundaries in RIAPS



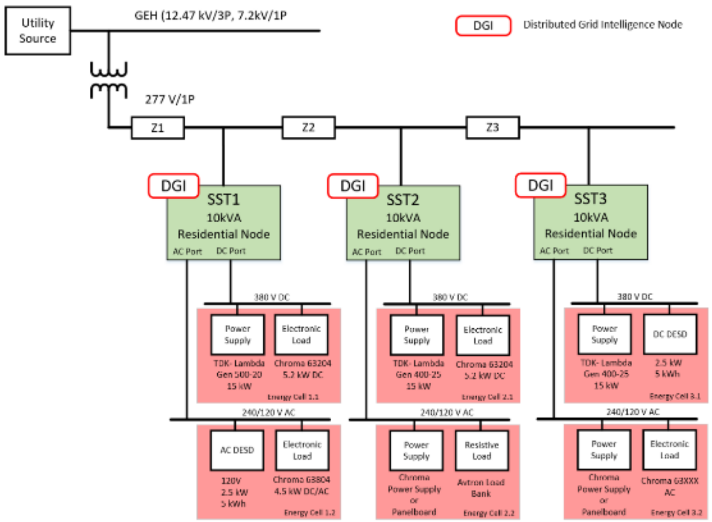
Microgrid Control System Implementation



- Primary Control implemented on Texas Instruments F28377S MCU
- Inverter power stage simulated in Opal FPGA (switching model, step time 0.5μs); microgrid simulated on CPU (100μs)
- Custom-designed board allows for four DERs to be emulated
- Next steps: (1) Increase system size to 10+ nodes (2) Implement dynamic boundaries algorithm in HIL microgrid

FREEDM SST Testbed

- Moving towards a hardware implementation using FREEDM solid-state transformer (SST) hardware testbed
- Testbed consists of 3 SSTs, 3 ESS, smart house, house loads, programmable loads, etc.
- NCSU integrated RIAPS+MCU platform with SST and ESS power electronics hardware



Project Challenges

- **Past challenges:**
  - Many milestones required production of significant documentation → Focus on the essentials in documents
  - Complexity of software code based required for the platform is considerable → Use existing open-source packages (after careful analysis and testing)
- **Possible project challenges going forward:**
  - Testing and validation of the platform *outside of lab* will be a significant effort → Explore opportunities for field testing
  - Completion of documentation, including training materials → Prioritize

List of Achievements

https://riaps.isis.vanderbilt.edu/papers.html

RIAPS

- Dubey, Abhishek, Karsai, Gabor, Volgyesi, Peter, Metelko, Mary, Madari, Istvan, Tu, Hao, Du, Yuhua, and Lukic, Srdjan. Device Access Abstractions for Resilient Information Architecture Platform for Smart Grid. United States: N. p., 2018. Web. doi:10.1109/LES.2018.2845854.
- Keynote Forum: "Towards a Resilient Information Architecture Platform for Smart Grid: RIAPS", Gabor Karsai, 1st International Conference on Smart Grid Technologies, Singapore, September 11-12, 2017
- P. Volgyesi, A. Dubey, T. Krentz, I. Madari, M. Metelko, G. Karsai, "Time Synchronization Services for Low-Cost Fog Computing Applications", International Symposium on Rapid System Prototyping (RSP), Seoul, South Korea, 10/2017
- S. Eisele, G. Pettet, A. Dubey, G. Karsai, "Towards an Architecture for Evaluating and Analyzing Decentralized Fog Applications", Fog World Congress, Santa Clara, CA, 10/2017
- A. Dubey, G. Karsai, and S. Pradhan, "Resilience at the Edge in Cyber-Physical Systems", The 2nd International Conference on Fog and Mobile Edge Computing, Valencia, Spain, IEEE, May 8-11, 2017
- S. Eisele, I. Madari, A. Dubey, and G. Karsai, "RIAPS: Resilient Information Architecture Platform for Decentralized Smart Systems", 20th IEEE International Symposium on Real-Time Computing, Toronto, Canada, IEEE, May 16-18, 2017
- W. Emfinger, A. Dubey, S. Eisele, P. Volgyesi, J. Sallai, G. Karsai, "Demo Abstract: RIAPS - A Resilient Information Architecture Platform for Edge Computing", The First IEEE/ACM Symposium on Edge Computing, SEC2016, DC, October 27-28, 2016
- Karsai, "Smart Grid & Fog: Taking Steps Towards A Prototype Software Platform for Fog Computing", OpenFog Consortium, May 4, 2017 https://www.openfogconsortium.org/smart-grid-fog-taking-steps-towards-a-prototype-software-platform-for-fog-computing

List of Achievements

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RAS

- R. Liu, A. Srivastava, A. Askerman, D. Bakken and P. Panciatici, "Decentralized State Estimation and Remedial Control Action for Minimum Wind Curtailment Using Distributed Computing Platform", 2016 IEEE Industry Applications Society (IAS) Annual Meeting, Portland, Oregon, October 2-6, 2016
- V.V.G Krishnan, R.Liu, A.Askerman, A.Srivastava, D.Bakken, and P. Panciatici, “Resilient Cyber Infrastructure for the Minimum Wind Curtailment Remedial Control Scheme” IAS Annual Meeting, Cincinnati, USA, 2017.
- R. Liu, A. Srivastava, D. Bakken, A. Askerman, and P. Panciatici, “Decentralized State Estimation and Remedial Control Action for Minimum Wind Curtailment Using Distributed Computing Platform,” IEEE Transactions on Industry Applications, Volume 53, Issue 6, Nov-Dec 2017, accepted 17 August 2017, pp. 5915-5926
- J. Xie and C.-C. Liu, “Multi-agent systems and their applications,” Journal of International Council on Electrical Engineering, vol. 7, no. 1, pp. 188–197, 2017.
- J. Xie, C.-C. Liu, and M. Sforna, “Agent-based distributed underfrequency load shedding,” 19th Intell. Syst. Appl. Power Syst. (ISAP ’17), San Antonio, Texas, USA, Sep. 2017.
- J. Xie, and C.-C. Liu, "Distributed Control by Multi-Agent Systems", Invited Session Presentation, Innovative Smart Grid Technologies (ISGT) Asia 2016, Melbourne, Australia, November 28 – December 1, 2016
- Krishnan, V. V. G., S. Gopal, Z. Nie, and A. Srivastava. "Cyber-power testbed for distributed monitoring and control." In *2018 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES)*, pp. 1-6. IEEE, 2018.

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Microgrid

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Tech to Market Path and IAB

- **Objective**
  - Open-source platform, supported by a spin-off
- **Market segment**
  - Power system software developers and users
- **Commercial partners/advisors**
  - ABB, Cisco, Duke Energy, National Instruments, RTE France, National Grid, OSISoft, Siemens, South California Edison, TVA
- **Activities**
  - Project is open-sourced (https://github.com/RIAPS, Apache License)
  - Collaboration with Linux Foundation/Energy Foundation
    - RIAPS is an LFEnergy project (https://www.lfenergy.org/)
  - Exploring field test opportunities with industrial partner
    - VMWare/Palo Alto microgrid effort

Plans

- **Next steps:**
  - Completion the testing of security features
  - Completion of documentation + training materials
  - Complete improved distributed applications (RAS, microgrid control, transactive energy, etc.)
- **Interactions:**
  - Started discussions with VMware about potential field testing and technology exchange